Compact High-Voltage Pulsed Power Source for Micropropulsion and Fast Electro-Optic Switching

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OUTLINE

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INTRODUCTION

Power conversion from light and heat is a well known important issue for many technical field. Photovoltaic and thermoelectric devices are commercially available for applications that require low voltage. Fundamental limit on voltage in a standard photovoltaic cell is imposed by the energy band gap, and is of the order of several volts. Efficiency of power conversion in photo and thermoelectric devices is now close to its maximum thermodynamic values.

For high-voltage and more efficient power conversion we suggest to use functionally graded materials and photogalvanic (or giant photovoltaic) effect, known for asymmetric materials.

We will discuss two methods of power generation:

1. With functionally graded materials (using time modulated and spatially structured optical or IR radiation);
2. Using homogeneous asymmetric materials with homogeneous illumination and photo- and thermogalvanic effects

Transient Photovoltaic Power Conversion

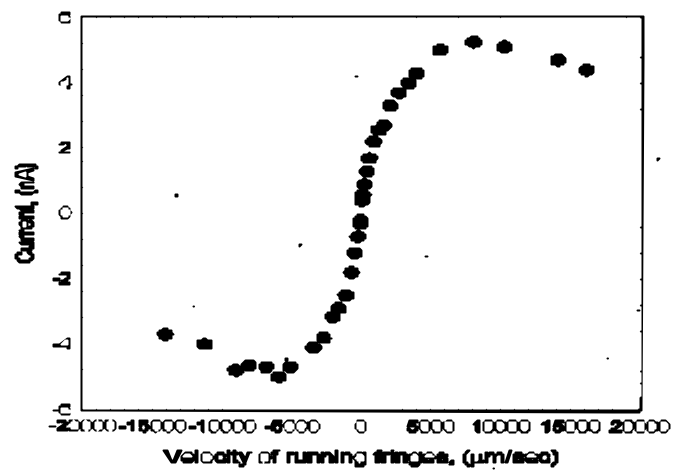
TRANSIENT FUNCTIONALLY GRADED MATERIALS

- Materials that spatially modulated (graded) by photoexitation or illuminated by structured IR pattern

The previous investigations showed that spatially modulated light (interference pattern) for can generate electrical current in the photosensitive materials.
This effect of Holographic current or Holographic Photo Electro Motive Force (HPEMF) is used for a remote sensing of small vibrations and for non-contact nondestructive testing.
We have developed theoretical model of the transient thermoelectric effect for power conversion.
This theoretical model predicts that transient thermoelectric effect may be more efficient for power conversion than traditional (steady-state) thermoelectric effect especially for a high intensity of IR radiation

PHOTOGALVANIC EFFECT

For asymmetric materials (without center of inversion) photogalvanic effect may contribute to the photoelectric current. Photogalvanic (or anomalous or giant photovoltaic effect (PGE)) is generation of photocurrent in homogeneous material under homogeneous illumination.



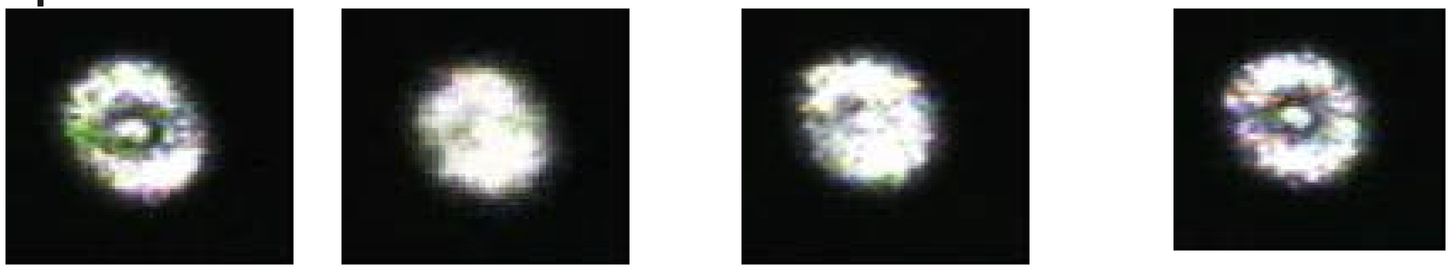
HOLOGRAPHIC CURRENT IN BSO CRYSTAL (ë = 514 nm)

The similar results we have observed in photorefractive semiconductor CdTe in IR

PHOTOGALVANIC EFFECT

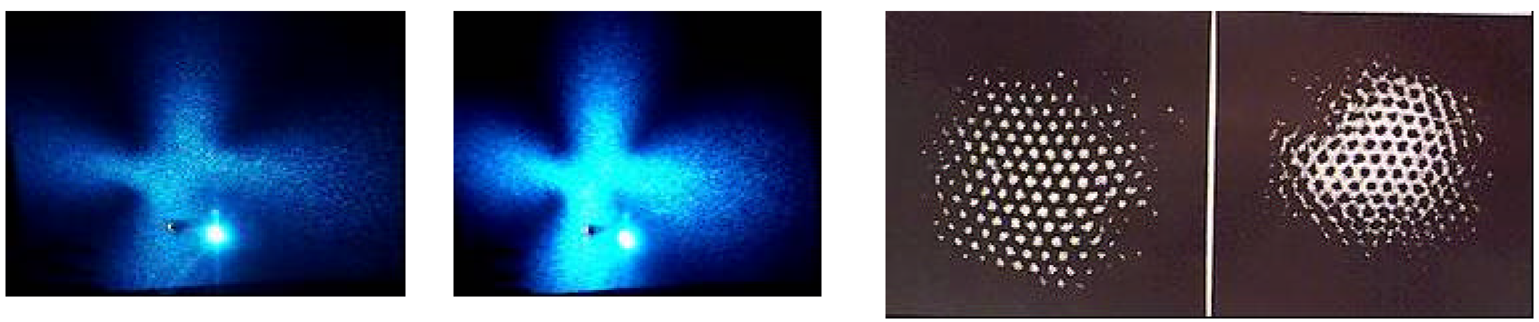
- In ferroelectric materials (KNbO3, LiNbO3, BaTiO3) high voltage (~103-105 V/cm) can be generated with moderate light intensity (~100mW)
- Originally PGE was discovered during investigation of an optical data storage using holographic methods.
- In our experiments with ferroelectric materials KNbO3 :Fe and LiNbO3 :Fe illuminated by laser light we have observed optical pulsations At the same time pulsating electrical signals from the attached electrodes was also detected.

OPTICAL PULSATIONS

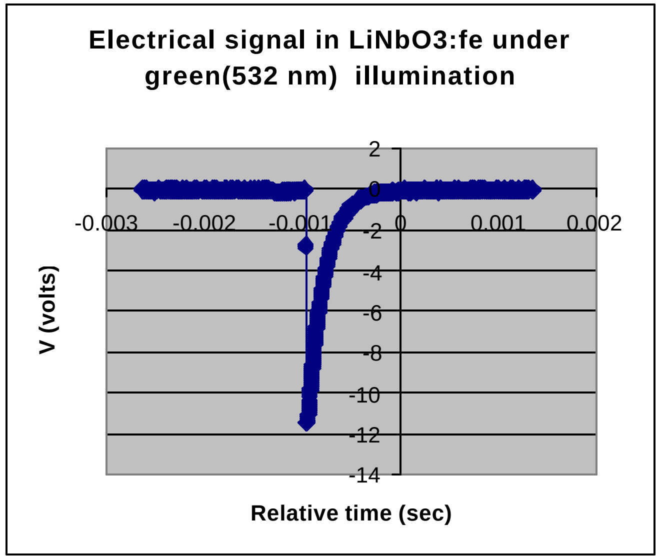


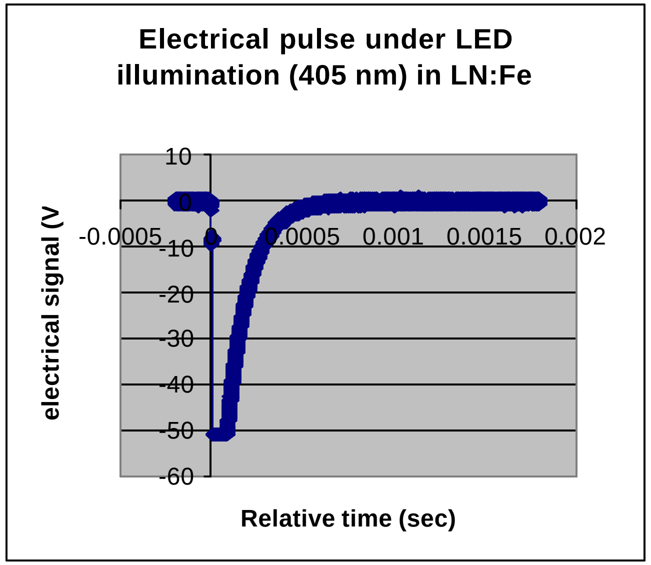
Time sequence of self-pulsations of back-scattered laser beam in photorefractive $LiNbO_3$:Fe

For the focused laser beam we have observed spectacular selforganized patterns

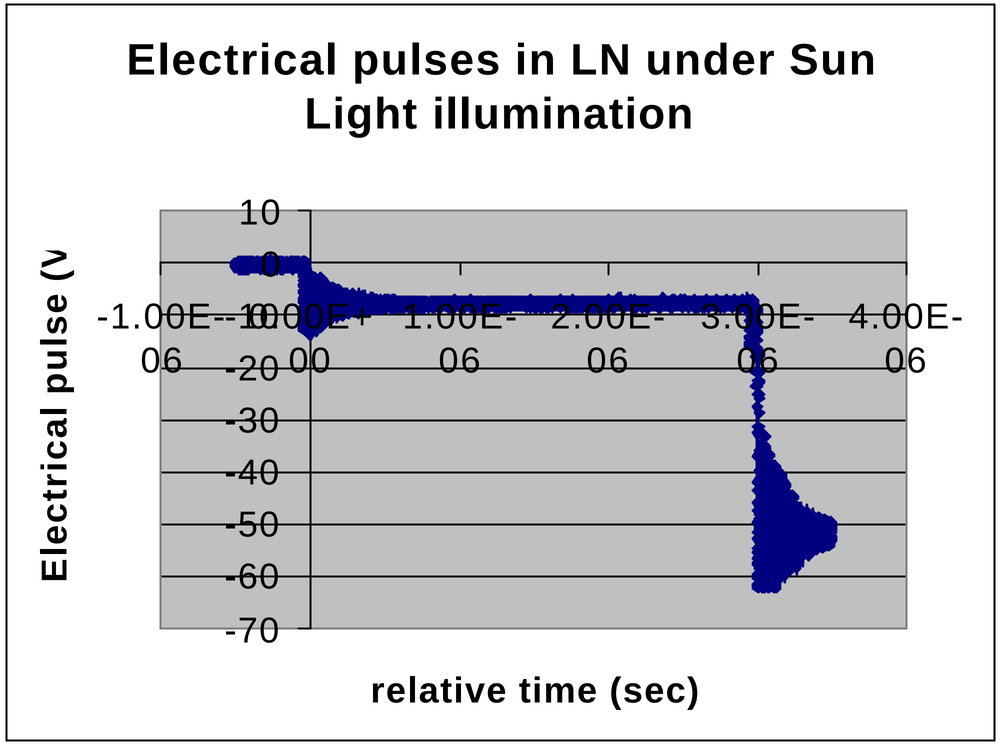


Electrical Pulsations





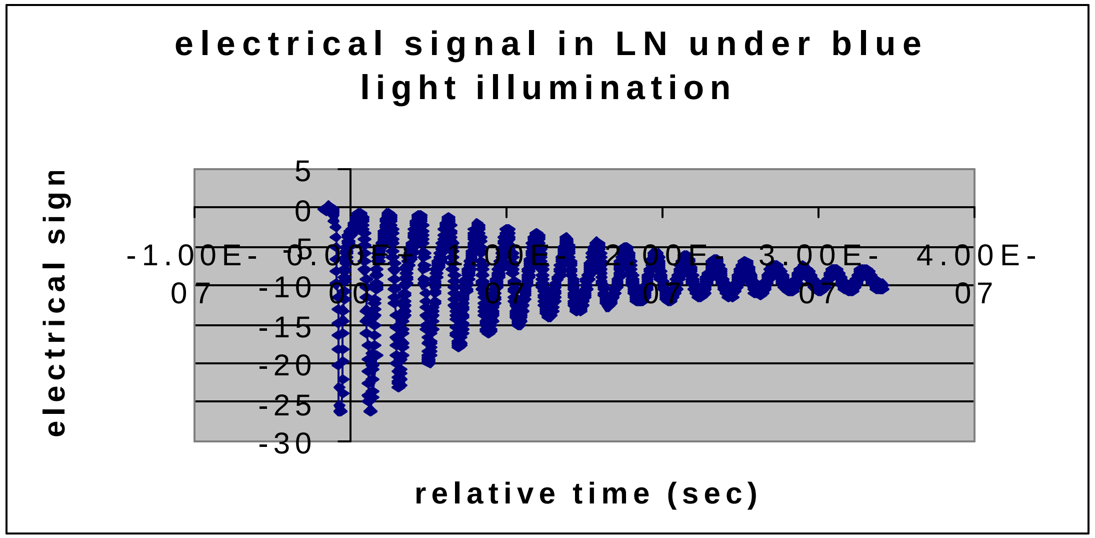
Electrical Pulsations



Maximum signal on oscilloscope with the 1 MÙ input was about 60V. This means that instant power was about 3. 6 mW.

Electrical Pulsations

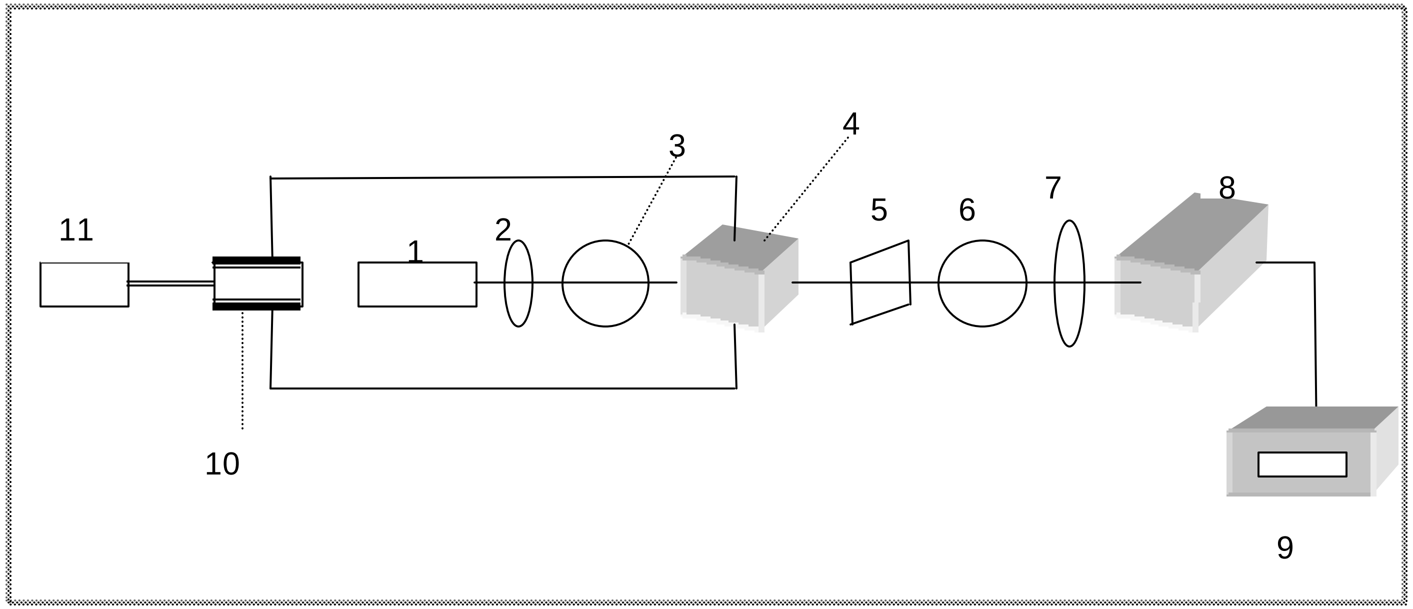
Electrical pulses look like decaying oscillation with a period ~1 nsec, total pulse width is about 0.5 msec. Repetition rate depends on intensity and varied from 10 to 0.1 HZ



Due to high resistivity of the $LiNbO_3$ crystal (~10^9 – 10^{12} Ù) pulses of current with 50 mA can generate high voltage (10^3 – 10^5 V/cm) on the high impedance load.

High Voltage Signal Confirmation

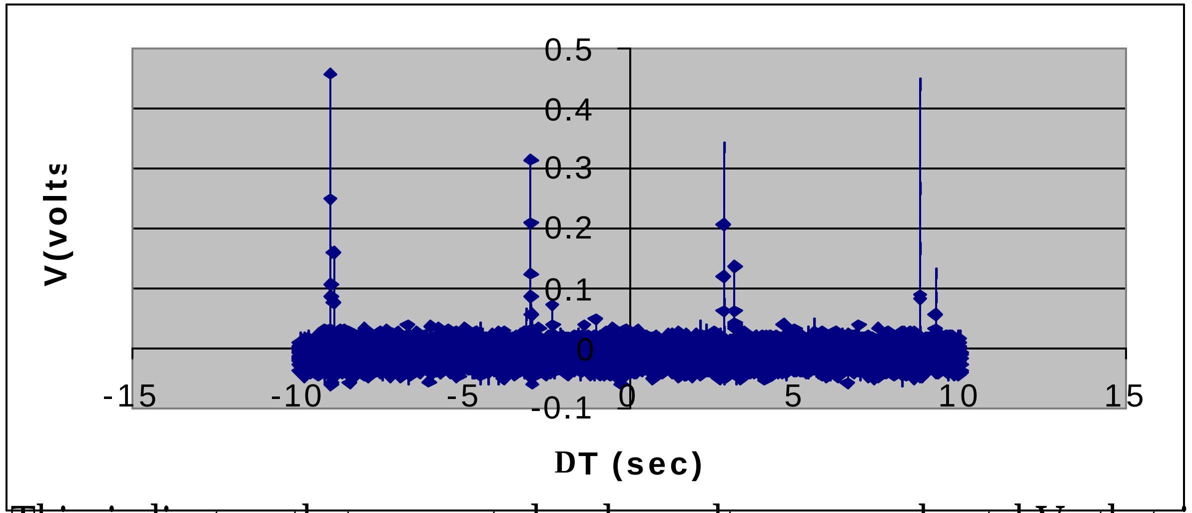
The high voltage signal has been confirmed by experiment with the standard modulator based on the $Bi_{12}SiO_{20}$ electro-optical crystal.



Scheme of Electro-Optical Modulator.
1-HeNe laser, 2-focusing lens, 3-Polarizer, 4 – BSO crystal, 5- 1/4 wave plate, 6 – Analyser, 7 – Focusing lens , 8 – Photodetector, 9 – Digital oscilloscope, 10 – z-cut $LiNbO_3$:Fe with electrodes, 11 – Solid State Laser λ= 532 nm).

High Voltage Signal Confirmation

$LiNbO_3$ crystal as a power source for E-O Modulator.



This indicates, that generated pulse voltage was about kV, that is consistent with our estimations of the signals, expected on the high-resistance electro optic crystal.

Theoretical Approach

To explain electrical pulsations we have suggested a model that include photogalvanic effect, pyroelectric and thermoelectric effects due to temperature changes.

We first formulate the general form of the starting equations describing known and expected results from the standard PR model. Taking into account growing interest to the spatio-temporal patterns in different fields of modern science, we present the equations in the appropriate three-dimensional (3-D) form.

The system of equations for photogenerated mobile charged carriers with concentration n, photosensitive ionized centers N (which are fixed in space) and electrostatic field E may be written as

Theoretical Approach

$$\boldsymbol{J} = \boldsymbol{J} + \boldsymbol{e}_{\mathrm{o}}\boldsymbol{e}\frac{\partial \boldsymbol{E}}{\partial \boldsymbol{t}} + \boldsymbol{g}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} + \boldsymbol{j}_{\boldsymbol{ph}}$$

$$\boldsymbol{j} = \boldsymbol{emn}(\boldsymbol{E} + \frac{\boldsymbol{k}_{\boldsymbol{B}}\boldsymbol{T}}{\boldsymbol{en}} - \boldsymbol{b}\nabla \boldsymbol{T})$$

Here, $\boldsymbol{e}$ is the effective charge of the carrier, ì is mobility of the mobile carriers, , $\boldsymbol{b}$ is the thermal generation rate and $\boldsymbol{r}$ is recombination coefficient, $\boldsymbol{e}_{\boldsymbol{0}}$ is the dielectric constant of vacuum and $\boldsymbol{e}$ stands for the relative dielectric constants, $\boldsymbol{k}_{\mathrm{B}}$ is the Bolzmann constant.

For temperature:

$$\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} + \boldsymbol{a}\boldsymbol{I} + \boldsymbol{D}\nabla^2\boldsymbol{T} - (\boldsymbol{T} - \boldsymbol{T}^0)\boldsymbol{t}^{-1}$$

$\boldsymbol{a}$ is an effective absorption coefficient, $\boldsymbol{I}$ is the intensity of input (heating) radiation, $\boldsymbol{D}$ is the thermodiffusivity, $\boldsymbol{t}$ is the relaxation time for heat dissipation, and $\boldsymbol{T}^0$ is the ambient $\boldsymbol{T}$ of the sample.

Theoretical Approach

For electric field :

$$\nabla(\boldsymbol{ee}_0\boldsymbol{E}) = \boldsymbol{e}(\boldsymbol{N} - \boldsymbol{N}_A - \boldsymbol{n})$$

$\boldsymbol{N}$ is the total concentration of photosensitive centers, $\boldsymbol{N_A}$ is the concentration of compensating centers

For noncentrosymmetric materials the photogalvanic current term in the RHS of the first equation in :

$$\boldsymbol{j^p}_i = \boldsymbol{g}_{ijk}\boldsymbol{F}_j\boldsymbol{F}_k^*$$

where $\boldsymbol{g}$ is the photogalvanic tensor**,** and $\boldsymbol{F}_{j,k}$ are the electric-field components of the optical radiation.

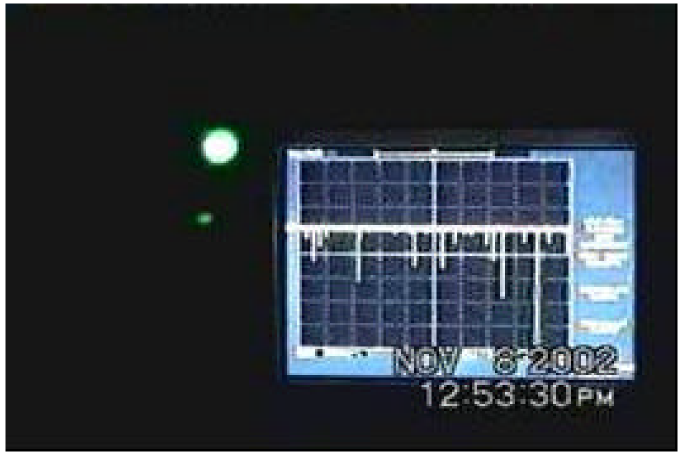
These equations with the equations for the plasma discharge current on the crystal-electrode interface were analyzed for the case of $LiNbO_3$ crystal. Without going into details we can say that this model allows to describe appearance of the electrical pulses and to give estimation of the pulse width and the repetition rate.

Actuation of Mechanical Movement of a macroscopic crystal by Low Power CW Laser

Recently we have demonstrated optical actuators based on photosensitive materials, controlled by moving holographic gratings that create moving electric-field pattern. As a step to more practical and robust actuator, we have realized single- beam optical scheme that allow us to transform energy of low-power CW laser into periodic mechanical movement of the macroscopic crystal sample. Basic principle of operation may be described as follows. Laser light from low power (P=100 mW) compact CW solid state laser (ë = 532 nm) illuminates z-cut crystal of $LiNbO_3$:Fe creating photogalvanic current Separation of charges due to this current create a strong electric field (100 kV/cm) that apply to the crystal and to adjacent metal electrodes. This strong electric field induces electrical discharges on the crystal surface and in the gaps between crystals and metal electrodes. High voltage (several kV) was generated in the internal load during these electrical instabilities. When crystal was free-standing (inclined at 5^0 from the vertical position) between the electrodes, these electrical pulses are accompanied by mechanical movement of the illuminated crystal. Periodical movement of crystal is sustained by a balance between electrical and gravitational forces. Movement of the crystal was detected by the reflection of the pumping laser beam from the crystal surface

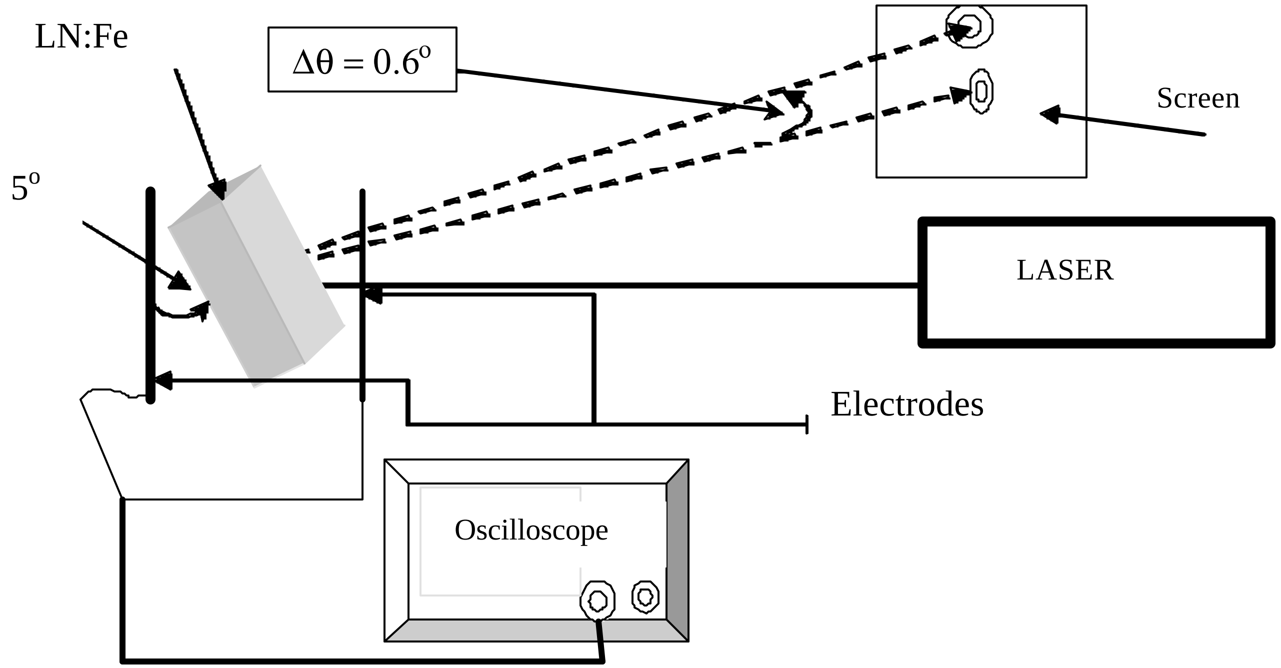
Actuation of Mechanical Movement of a macroscopic crystal by Low Power CW Laser

We have observed periodical movement of the crystal $LiNbO_3$:Fe (mass is 0.47 g) actuated by solid state CW laser. Oscillations with angular amplitude up to 0.6^0 was detected using capacitor type arrangement.



Oscillations of the reflected from the crystal surface optical signal (corner) and electrical signal as seen on the oscilloscope TDS3000B (for 1 MÙ input signals up to 15 V).Two pictures show that jump of reflected beam correlated with an electric pulse.

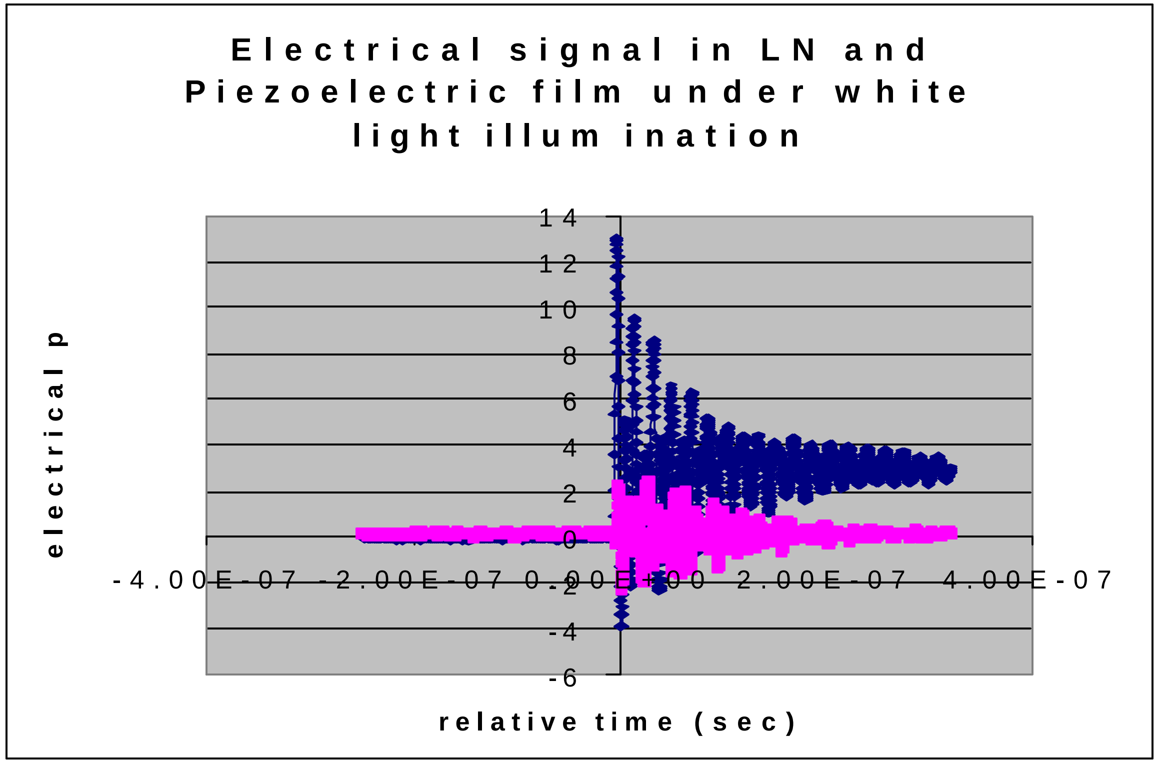
EXPERIMENTAL SETUP



Amplitude of the angular oscillations was about 0.6^0 as measured by amplitude of oscillation of the reflected laser spot on the screen. This means that upper edge of the crystal "jumped" on the distance of 0.1 mm during electrical discharges. Inclination angle of the crystal was about 5^0.

Actuation of Mechanical Movement of a macroscopic crystal by Low Power CW Laser

Another experiment to confirm mechanical movement of the $LiNbO_3$:Fe crystal during light illumination has been done. Piezoelectric film has been attached to rear surface of the $LiNbO_3$:Fe, the front surface has been illuminated by coherent (ë =532 nm) and incoherent white light. During illumination, two electrical signals have been observed.



CONCLUSIONS

- Compact pulsed photovoltaic power source can generate kV-nsec electrical pulses from the CW low-power illumination (laser, LED, fiber illuminator, Sun-light).
- Peak power from the Sun-light is ~ 3mW from the cell 2 x 2 cm.
- It was demonstrated that this pulsed source can drive standard high-speed EO modulator and piezoelectric element, some power emitted as a RF pulse
- In a low vacuum it is expected, that electron beam (due to Ferroelectric Electron Emission (FEE)) can be used as a neutralizer in the ion truster
- Actuation of the mechanical movement of the 6.8g crystal was demonstrated using pulsed photovoltaic source

PUBLICATIONS

- The main publications describing the phenomena are :
- N.Kukhtarev, T.Kukhtareva, P.Banerjee, (invited paper) “A Unified Treatment of Radiation induced Photorefractive, Thermal, and Neutron Transmutation Gratings, Proceedings IEEE, November 1999.
- N.Kukhtarev, T.Kukhtareva, M. Bayssie D.Frazier, B.Penn, H.Abdelaem et al i Photogalvanic pulsator, CLEO '2002, Technical Digest
- N.Kukhtarev, T.Kukhtareva, M. Bayssie D.Frazier, B.Penn, H.Abdelaem et al Photo-induced Optical and Electrical Pulsations and Pattern Formation in Photorefractive crystals, Proc. of SPIE, Annual Meeting, Seattle, (2002)
- N.Kukhtarev, T.Kukhtareva, M.Edwards B.Penn, D.Frazier, H.Abdeldayem, P.P. Banerjee, T.Hudson, W.A.Friday, Photoinduced Optical and Electrical High-Voltage Pulsations and Pattern Formation in Photorefractive crystals, (invited paper), JNOPM, Vol.11, No.4 (2002)

Acknowledgements

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